

# Counterflow measurements in strongly correlated GaAs hole bilayers: evidence for electron-hole pairing

E. Tutuc, M. Shayegan

*Department of Electrical Engineering, Princeton University, Princeton, NJ 08544*

D.A. Huse

*Department of Physics, Princeton University, Princeton, NJ 08544*

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We study interacting GaAs bilayer hole systems, with very small interlayer tunneling, in a counterflow geometry where equal currents are passed in opposite directions in the two, independently contacted layers. At low temperatures, both the longitudinal and Hall counterflow resistances tend to vanish in the quantum Hall state at total bilayer filling  $\nu = 1$ , demonstrating the pairing of oppositely charged carriers in opposite layers. The counterflow Hall resistance decreases much more strongly than the longitudinal resistances as the temperature is reduced.

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In closely spaced bilayer carrier systems, the combination of interlayer and intralayer Coulomb interaction leads to a host of novel phenomena with no counterpart in the single-layer case [1, 2, 3, 4, 5, 6, 7, 8]. A particularly remarkable phase is the quantum Hall state (QHS) formed at total Landau level filling factor  $\nu = 1$  in the limit of zero interlayer tunneling. This state possesses unique, interlayer phase coherence, and exhibits unusual properties, such as Josephson-like interlayer tunneling [6] and quantized Hall drag [7]. The  $\nu = 1$  QHS can be regarded as a condensate of excitons [5], that is pairs of electrons and holes in opposite layers. An alternative picture is to view the layer degree of freedom as pseudospin. In this picture, the  $\nu = 1$  QHS is a quantum Hall ferromagnet, where all pseudospins point in the same direction [8].

We report magneto-transport measurements on an independently contacted GaAs bilayer hole system in various geometries for the current injection and voltage detection. We experimentally prove the fundamental relations that are theoretically expected to hold between the various transport coefficients. Focusing on the "counterflow" configuration, we show explicitly that the counterflow Hall resistance at  $\nu = 1$  tends to vanish at low temperatures along with the longitudinal resistance. This observation provides direct evidence that the counterflow carriers have zero electrical charge or, equivalently, that they are electron-hole pairs in opposite layers. We also report unexpected behavior for the counterflow Hall resistance at  $\nu = 1$ : as the temperature is lowered, it drops quickly well below values of all other resistivities, including the counterflow longitudinal resistivity.

Our samples are Si-modulation-doped GaAs double-layer hole systems grown on GaAs (311)A substrates. They consist of two, 150Å wide, GaAs quantum wells separated by a 75Å wide AlAs barrier. We measured two samples from one wafer, both displaying consistent results; here we focus on data from one sample. We used Hall bars of 100μm width, aligned along the [011] crystal direction [9]. The Hall bar mesa, shown schematically

in Fig. 1(a), has two current leads at each end, and three leads for measuring the longitudinal and Hall voltages across the bar. Diffused InZn Ohmic contacts are placed at the end of each lead. We use a combination of front and back gates [10] to selectively deplete one of the layers around each contact, in order to probe the different transport configurations of the bilayer, i.e., single layer, drag or counterflow. As grown, the densities were  $p_T = 2.6 \times 10^{10} \text{ cm}^{-2}$  and  $p_B = 3.2 \times 10^{10} \text{ cm}^{-2}$  for the top and bottom layers, respectively. The mobility along [011] at these densities is approximately  $20 \text{ m}^2/\text{Vs}$ . Metallic top and bottom gates were added on the active area to control the layer densities. The measurements were performed down to a temperature of  $T = 30\text{mK}$ , and using low-current (0.5nA-1nA), low-frequency lock-in techniques.

Experimentally, several transport coefficients can be measured in a bilayer system [Figs. 1(b,c)]. In the "bilayer" configuration [Fig. 1(b), left], current is passed through both layers. We define the bilayer resistivities, longitudinal and Hall, by the corresponding voltage drops along or across the Hall bar, divided by the total current [11]. In counterflow measurements [Fig. 1(c) left] we selectively deplete one of the layers around each contact, so that that contact is connected to only one of the layers as indicated in Fig. 1(a). Two leads at one end of the Hall bar are used for driving a current in and out of the sample, while the leads at the opposite end are shorted, to ensure that the same current, but in the opposite direction, flows in both layers. Additionally, a current meter can be placed between the shorted leads to measure the interlayer current leakage. The resistivities measured in the counterflow configuration are defined as the corresponding voltage drops along or across the Hall bar divided by the current flowing in a single layer. This definition is adopted so that the counterflow transport coefficients become the same as the single layer ones, when the coupling between the layers is negligible.

The transport coefficients, longitudinal or Hall, of a single layer ( $\rho_{SL}$ ) are defined by the ratio between the

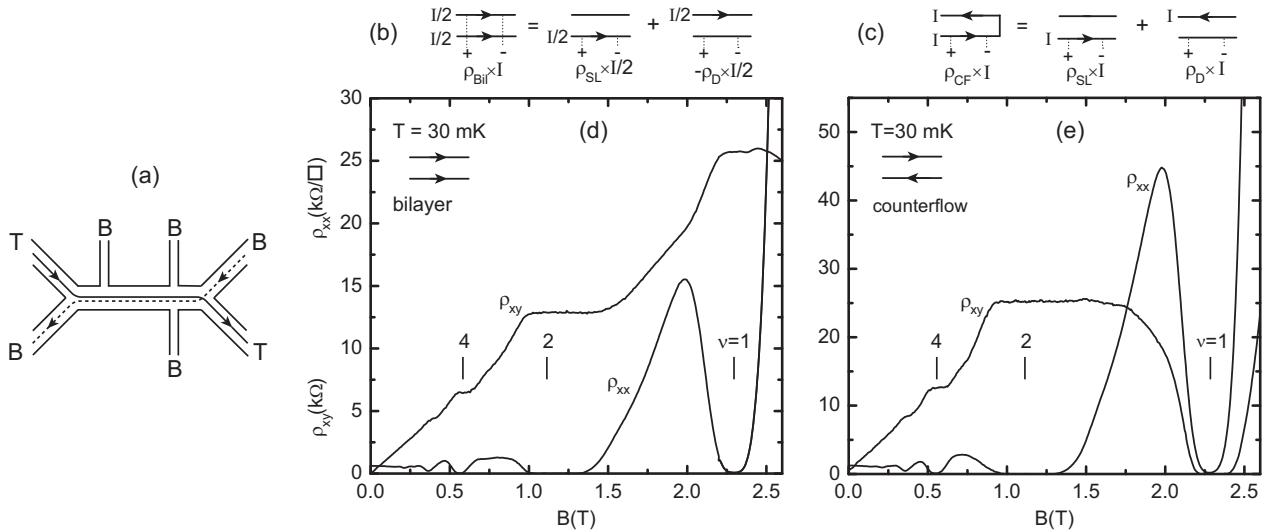


FIG. 1: (a) Schematic representation of the Hall bar mesa utilized in this study. Each lead contacts a particular layer (T-top; B-bottom) in the counterflow configuration. (b,c) Illustration of the relations between the bilayer, counterflow, single layer and drag voltages and related transport coefficients. (d)  $\rho_{xx}$  and  $\rho_{xy}$  measured at  $T = 30$  mK in the bilayer configuration where all contacts are made to both layers. (e)  $\rho_{xx}$  and  $\rho_{xy}$  measured in the bottom layer in the "counterflow" configuration where equal and opposite currents are passed in the two layers. In (d) and (e) the layer densities are  $p_B = p_T = 2.75 \times 10^{10} \text{ cm}^{-2}$ .

corresponding voltage drops and the current flowing in that layer, when no current flows in the opposite layer. Additionally, a current flowing in one layer will induce a voltage drop in the opposite layer. The drag transport coefficients ( $\rho_D$ ) are defined by the corresponding voltage drops in one (drag) layer, divided by the current flowing in the opposite (drive) layer [12]. As depicted in Figs. 1(b,c) the bilayer ( $\rho_{Bil}$ ) and counterflow ( $\rho_{CF}$ ) transport coefficients (both longitudinal and Hall) are related to the single layer and drag coefficients:  $\rho_{Bil} = (\rho_{SL} - \rho_D)/2$  [13] and  $\rho_{CF} = \rho_{SL} + \rho_D$ . The validity of these relations is indeed seen in our data and serves as a consistency check for our measurements.

The highlight of our results is illustrated in Figs. 1(d,e) where the longitudinal ( $\rho_{xx}$ ) and Hall ( $\rho_{xy}$ ) resistivities are shown vs perpendicular magnetic field ( $B$ ). In Fig. 1(d) we plot the data taken in the bilayer configuration, when both the current and voltage leads are contacting both layers. The data of Fig. 1(d) show a strong QHS at  $\nu = 1$ , evidenced by a vanishing  $\rho_{xx}$  and a well developed Hall plateau at  $h/e^2 \simeq 25.8$  k $\Omega$ . A main finding of our study is contained in Fig. 1(e) where, in the counterflow geometry,  $\rho_{xx}$  and  $\rho_{xy}$  are measured on the bottom layer, while a current of equal value flows in the *opposite* direction in the other layer. The data of Fig. 1(e) show that for the  $\nu = 1$  QHS, both  $\rho_{xx}$  and  $\rho_{xy}$  tend to vanish. The vanishing Hall resistivity is particularly noteworthy, since it directly proves that the counterflow current at  $\nu = 1$  is transported by neutral carriers, that is, pairs of electrons and holes in opposite layers (excitons). Indeed, an electron-hole pair moving in one direction will create equal and opposite currents in the two layers.

In Fig. 2 we show the  $T$  dependence of  $\rho_{xx}$  measured

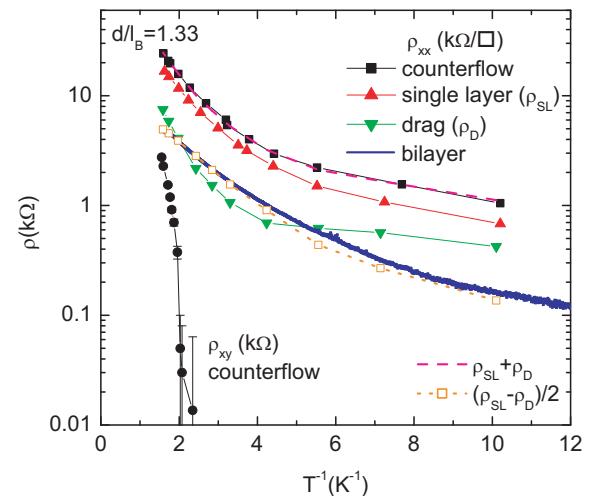


FIG. 2: (Color online)  $T$  dependence of various transport coefficients at  $\nu = 1$ : counterflow, single layer and drag  $\rho_{xx}$ 's, and counterflow  $\rho_{xy}$ . Remarkably, the counterflow  $\rho_{xy}$  remains much smaller than the counterflow  $\rho_{xx}$  in the entire  $T$ -range. The two linear combinations of single layer and drag longitudinal resistivities,  $(\rho_{SL} - \rho_D)/2$  and  $\rho_{SL} + \rho_D$ , are also shown.

at  $\nu = 1$  in different configurations: counterflow, single (bottom) layer, drag, and bilayer. We also plot the counterflow  $\rho_{xy}$  vs  $T$ , and show the two linear combinations of single layer and drag longitudinal resistivities,  $(\rho_{SL} - \rho_D)/2$  and  $\rho_{SL} + \rho_D$ . The validity of the relations  $\rho_{Bil} = (\rho_{SL} - \rho_D)/2$  and  $\rho_{CF} = \rho_{SL} + \rho_D$ , apparent from Fig. 2, affirms the consistency of our data [14]. The

data of Fig. 2 show a decrease of  $\rho_{xx}$  with decreasing  $T$ , exhibiting an approximately exponential dependence at higher temperatures followed by a weaker variation at lower  $T$ . This weaker  $T$ -dependence could stem from sample disorder, a competition between the  $\nu = 1$  QHS and the neighboring reentrant insulating phase [15], or a lack of thermalization of the carriers. The energy gap of the  $\nu = 1$  QHS, obtained by fitting an exponential dependence  $\rho_{xx} \propto \exp(-\Delta/2T)$  at higher  $T$  to the bilayer resistivity, is  $\Delta = 1.3\text{K}$ , in good agreement with previously reported results [15]. A parameter relevant to the physics of the  $\nu = 1$  QHS is the ratio  $d/l_B$  between the interlayer spacing ( $d$ ) and the magnetic length ( $l_B = \sqrt{\hbar/eB}$ ) at  $\nu = 1$ . This parameter, which is a measure of the ratio of the intralayer and interlayer interaction energies, is  $d/l_B = 1.33 \pm 0.1$  for the data shown here. The error in determining  $d/l_B$  stems from variations of the growth rates across the sample wafer, which was not rotated during the growth.

A striking finding of our study is the  $T$ -dependence of the counterflow  $\rho_{xy}$ . As  $T$  is increased, the counterflow  $\rho_{xy}$  remains much smaller, roughly by an order of magnitude, than the counterflow  $\rho_{xx}$ . This demonstrates that the electron-hole pairing, a prerequisite for the stabilization of this peculiar QHS, is considerably stronger than the  $\nu = 1$  QHS itself. Indeed, an exponential fit  $\rho_{xy} \propto \exp(-\Delta_H/2T)$  to the counterflow  $\rho_{xy}$  vs  $T$ , yields an apparent energy gap  $\Delta_H = 9.5\text{K}$ , much larger than the one obtained from the  $T$ -dependence of  $\rho_{xx}$ .

To better visualize the strength of the counterflow  $\rho_{xy}$  at  $\nu = 1$ , in Fig. 3(a) we show counterflow and bilayer  $\rho_{xx}$  and counterflow  $\rho_{xy}$  vs  $B$ , measured at  $T = 630\text{mK}$ . The data clearly show that the counterflow  $\rho_{xx}$  is roughly an order of magnitude larger than  $\rho_{xy}$  at  $\nu = 1$ . In Fig. 3(b), we show  $\rho_{xy}$  vs  $B$  traces measured for a single (bottom) layer as well as the Hall drag. As shown in Fig. 3(a), there is excellent agreement between the counterflow  $\rho_{xy}$  and the sum of the two traces of the bottom panel. The fact that the drag and single layer  $\rho_{xy}$  are very close to the quantized  $h/e^2$  value even at this high temperature, confirms our finding that the counterflow  $\rho_{xy}$  is small.

An important aspect of the drag and counterflow measurements is the current leakage between the layers. In our counterflow experiments, at a current of  $0.5\text{nA}$ , the interlayer leakage at  $\nu = 1$  is  $\simeq 4\%$  at  $T = 30\text{mK}$  and tends to increase almost quadratically with  $T$ , reaching about 8% of the total current at  $T \simeq 600\text{mK}$ . The leakage also increases at larger currents. Moreover, we observe smaller but comparable leakage at other fillings, especially when the in-plane resistivity is large. Based on these observations we believe that Josephson-like tunnelling [6] is not the main source of leakage at  $\nu = 1$ . It is unclear, however, if the leakage in our samples stems from conventional tunnelling across the AlAs barrier between the layers or happens at particular locations (e.g., defects in the barrier). In the counterflow measurements, the interlayer leakage translates to a small reduction of the actual counterflow current. In the drag measurements, the

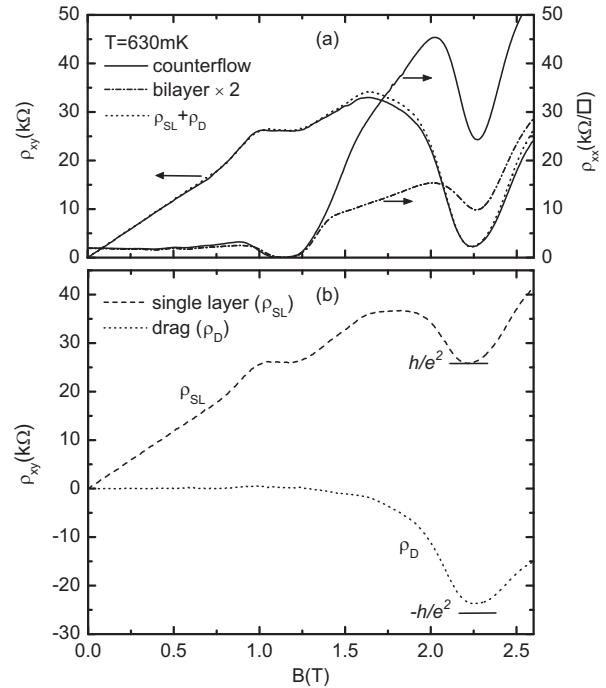


FIG. 3: (a) Counterflow  $\rho_{xx}$  and  $\rho_{xy}$ , bilayer  $\rho_{xx}$ , and (b) single (bottom) layer  $\rho_{xy}$  and Hall drag vs  $B$ , all measured at  $T = 630\text{mK}$ . As a consistency check, the sum of these two traces is shown in panel (a) as a dotted trace. The bilayer  $\rho_{xx}$  is multiplied by 2 to normalize it to the *layer* current.

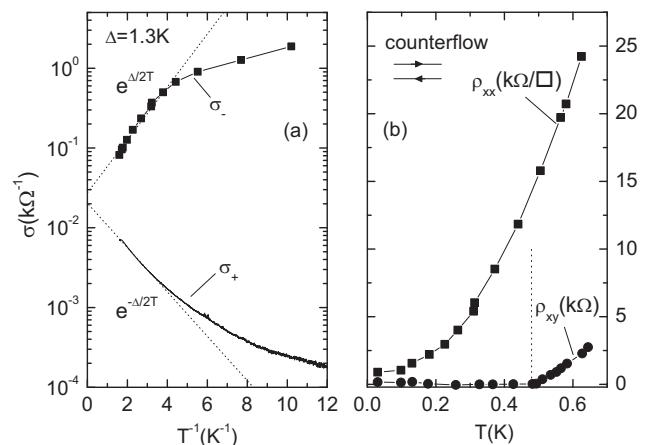


FIG. 4: (a) Symmetric ( $\sigma_+$ ) and antisymmetric ( $\sigma_-$ ) conductivities vs  $T^{-1}$  measured at  $\nu = 1$ . (b) Counterflow  $\rho_{xx}$  and  $\rho_{xy}$  vs  $T$ .

error in the data resulting from the interlayer leakage can be deduced by changing the ground contact of the drag layer and recording the change in the drag signal; at the highest temperatures ( $T \simeq 630\text{mK}$ ), where the interlayer leakage is the largest, this error is  $\pm 8\%$  for  $\rho_{xx}$  and  $\pm 2\%$  for  $\rho_{xy}$ . We emphasize that these errors do not change any of our overall conclusions.

The resistivities  $\rho_{xx}$  and  $\rho_{xy}$  measured in the bilayer and counterflow configurations can be converted to conductivities, following the usual tensor inversion. The results represent the symmetric (bilayer),  $\sigma_+$ , and antisymmetric (counterflow),  $\sigma_-$ , channel conductivities [16]. The data are shown in Fig. 4(a).  $\sigma_+$  decreases with decreasing  $T$ , while  $\sigma_-$  increases with decreasing  $T$ . At higher temperatures their dependence on  $1/T$  is approximately exponential with an energy gap of  $\Delta = 1.3K$ , followed by a saturation at lower temperatures. At the lowest temperatures the antisymmetric conductivity is approximately four order of magnitude larger than the symmetric one. This dependence is a direct consequence of the fact that the counterflow  $\rho_{xy}$  is much smaller than the bilayer Hall resistivity, which has a value of  $h/e^2$  approximately, nearly independent of temperature. We also note that, while  $\sigma_+ \ll \sigma_-$ , the counterflow configuration is actually more dissipative than the bilayer one because of its higher longitudinal resistivity.

In Fig. 4(b) we show the counterflow  $\rho_{xx}$  and  $\rho_{xy}$  vs  $T$  on a linear scale. The  $T$  dependence of the counterflow  $\rho_{xy}$  is striking. As the  $T$  is increased from 30mK to 0.5K,  $\rho_{xy}$  remains small, even though  $\rho_{xx}$  increases considerably in this  $T$  range. The counterflow  $\rho_{xy}$  starts to sharply increase at  $T = 0.5K$ . Is this feature at about 0.5K the theoretically-predicted [5], but not yet observed Kosterlitz-Thouless (KT) transition expected for this system? If so, the observed behavior is not as expected, since there is no sign of a transition in the counterflow  $\rho_{xx}$ . The proposed KT transition is the unbinding of vortex pairs. The vortices are low-energy collective excitations of the correlated bilayer QHS; they are vortices in a superfluid condensate of neutral interlayer excitons [5]. When they are unbound, the vortices move across the counterflow current and produce phase-slip and thus

a longitudinal resistance. We suspect that unpaired vortices remain present in our samples to the lowest  $T$  we study (perhaps due to disorder effects) and their mobility produces the nonzero  $\rho_{xx}$ . Below  $T = 0.5K$  their average motion is nearly perpendicular to the counterflow current, so the counterflow Hall angle is very near zero. In this scenario, the strong increase in  $\rho_{xy}$  above 0.5K is an unbinding of the neutral interlayer excitons into uncorrelated charges that can move independently in each layer and thus produce a counterflow Hall resistance. The much stronger  $T$  dependence of  $\rho_{xy}$  than  $\rho_{xx}$  would then imply that the energy to unbind an exciton into independent charges in each layer that produce a Hall resistance is much larger than the energy (either an unbinding or a pinning energy) to produce mobile vortices and thus a longitudinal resistance.

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Note added - During the writing of this manuscript, a report on similar experiments in a GaAs electron bilayer appeared [17]. In Ref. [17] a vanishing of the counterflow  $\rho_{xx}$  and  $\rho_{xy}$  at low  $T$  is also observed but, unlike our data, the  $T$ -dependences of these coefficients appear to be very similar. While we do not know the reason for this difference in behavior, we mention three factors that distinguish our bilayer hole system from the bilayer electron system studied in [17]: (i) the estimated interlayer tunneling in the hole system is about one order of magnitude smaller, because of the heavier GaAs hole effective mass, (ii) the parameter  $d/l_B = 1.33$  is smaller for our sample, placing it deeper in the  $\nu = 1$  bilayer quantum Hall phase (iii) the mobility anisotropy [9] could affect the current distribution in the GaAs 2D hole samples, and possibly change the Hall angle.

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[11] The longitudinal resistivity is the measured longitudinal resistance divided by four, the number of squares between the voltage probes in our sample.  
[12] We employ the following convention for the sign of the drag resistivities: the drag resistivity, whether longitudinal or Hall, is positive when it has the *opposite* sign to the voltage drop in the drive layer.  
[13] This relation is strictly valid if the layers are identical.  
[14] While our sample design does not allow us to directly measure the top layer transport coefficients, the validity of the relation  $\rho_{Bil} = (\rho_{SL} - \rho_D)/2$ , apparent from Fig. 2, implies that the layers have very close resistivities.  
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[16] The counterflow resistivities should be divided by 2, in order for the tensor inversion to represent the antisymmetric channel conductivities. This is because we have defined the counterflow resistivities using the layer current and not the total current, which is twice larger.  
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